

Oxidation of Methyl Podocarpate and Methyl 12-Hydroxyabietan-8,11,13-trien-18-oate with Thallium(III) Perchlorate

Tatsuhiko Nakano,* María Isabel Hernández, Jose Manuel Polachini, Dinorah Avila Peña, and Edgar Corothie†

Centro de Química, Instituto Venezolano de Investigaciones Científicas (I.V.I.C.), Apartado 21827, Caracas 1020-A, Venezuela

Anibal Rojas

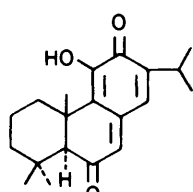
Escuela de Química, Facultad de Ciencias, Universidad Central de Venezuela, Caracas, Venezuela

Andrew T. McPhail*

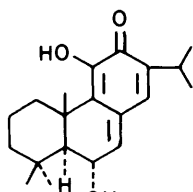
Department of Chemistry, P. M. Gross Chemical Laboratory, Duke University, Durham, North Carolina 27706, U.S.A.

On oxidation with thallium(III) perchlorate in aqueous perchloric acid, methyl podocarpate (**5**) yielded two products which were identified on the basis of spectral data as the *p*-quinol (**8**) and the aryl ketone (**7a**) which resulted from oxidation at C-7 remote from the aromatic ring *c*. When methyl 12-hydroxyabietan-8,11,13-trien-18-oate (**6**) was treated with the same reagent, a similar benzylic oxidation occurred yielding two aromatic compounds which spectroscopic analysis showed to be the aryl ketone (**11**) and the lactone (**12**) with a rearranged skeleton. The structure and stereochemistry of the latter product were established unequivocally by an X-ray crystallographic analysis. Possible mechanisms for the formation of compounds (**7a**), (**11**), and (**12**) are proposed.

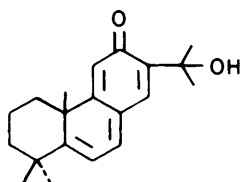
In addition to a number of naturally occurring quinoid diterpenes, such as taxodione (**1**), taxodone¹ (**2**), and fuerstione² (**3**) and its congeners, compound³ (**4**) has recently



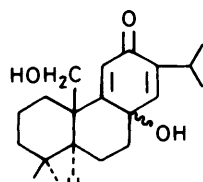
(1)



(2)



(3)



(4)

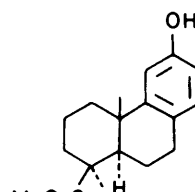
been found in *Austrocedrus chilensis* (D. Don) Florin and Boutelje (Cupressaceae). These quinoids may be regarded as being formed from their phenolic precursors by oxidation under biogenetic conditions. In view of the observed antitumour activity of these compounds and other quinone methides,⁴ we were interested in transforming podocarpic acid and its related compounds into other biologically active derivatives.

Results and Discussion

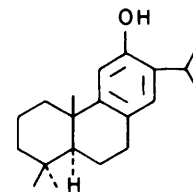
The utility of thallium(III) salts⁵ as excellent agents for the oxidation of a variety of organic substrates is well demon-

strated. Recent interesting reports^{6a,b} on the synthesis of *p*-quinols from some phenolic compounds by use of thallium(III) perchlorate persuaded us to investigate the oxidation of methyl podocarpate (**5**) and methyl 12-hydroxyabietan-8,11,13-trien-18-oate (**6**) with this reagent.

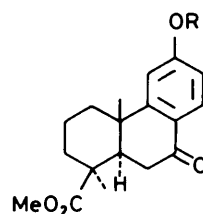
When methyl podocarpate (**5**) in methylene chloride was treated at room temperature for 45 min with thallium(III) perchlorate in aqueous perchloric acid, three compounds were isolated after chromatography over silica gel. The least polar material (24% yield) was eluted with benzene and was identified as methyl podocarpate (**5**). Elution with 5% diethyl ether in benzene yielded two products the less polar of which was isolated in 18.6% yield. This compound, C₁₈H₂₄O₄ [*m/z* 304 (*M*⁺)], was presumed to result from oxidation of ring *c* and was assigned to the *p*-quinol structure (**8**). The i.r. spectrum showed bands at 3 370 (OH), 1 725 (CO₂Me), and 1 665 cm⁻¹ (quinoid



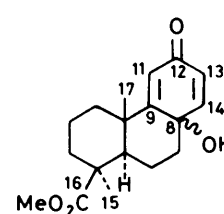
(5)



(6)



(7) a; R = H
b; R = Ac



(8)

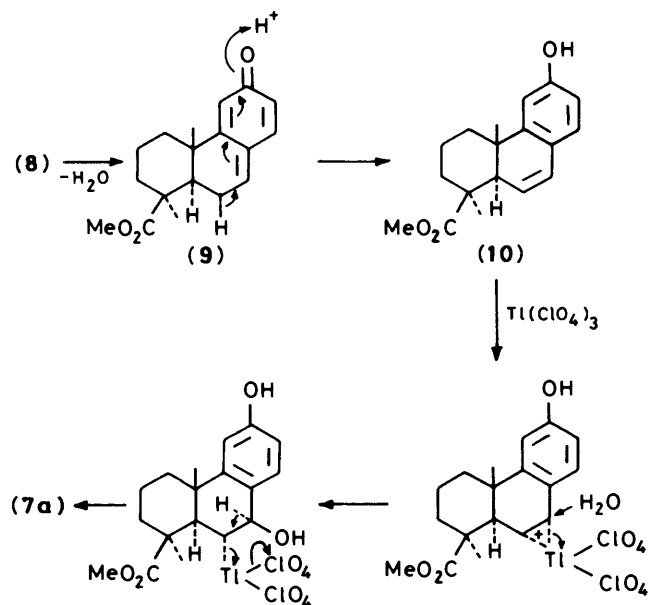
† Visiting scientist from Universidad Central de Venezuela, Caracas, 1982–84.

CO). More decisive evidence came from the ^1H and ^{13}C n.m.r. data. The ^1H n.m.r. signals at δ 5.96 (1 H, d, J 2 Hz), 6.03 (1 H, dd, J 10 and 2 Hz), and 6.70 (1 H, d, J 10 Hz) were attributed to hydrogen atoms at C-11, C-13, and C-14, respectively, in the *p*-quinol system. In accordance with these ^1H n.m.r. results, C-8, C-9, C-11, C-12, C-13, and C-14 resonated at δ 57.4, 169.7, 121.5, 186.8, 124.5, and 155.0 respectively.

The second, more polar product, obtained in 11.3% yield, was characterised as the acetate, $\text{C}_{20}\text{H}_{24}\text{O}_5$ [m/z 344 (M^+)], and formulated as (7b) on the basis of spectroscopic evidence. The integrity of the original aromatic ring c was elucidated from the ^1H and ^{13}C n.m.r. spectra. The ^1H n.m.r. signals at δ 6.86–7.20 (m) corresponded to two aromatic protons, at C-11 and C-13, and the remaining proton, at C-14, was detected at δ 8.06 as a doublet (J 8 Hz). The ^{13}C resonances for C-8, C-9, C-11, C-12, C-13, and C-14 were observed at δ 127.9, 155.0, 118.5, 156.3, 120.3, and 128.2, respectively. In addition to bands for an acetate (1760 cm^{-1}) and a CO_2Me group (1720 cm^{-1}), the i.r. spectrum contained an α,β -unsaturated ketone band at 1680 cm^{-1} , and this newly formed carbonyl group, which resonated at δ 196.67 in the ^{13}C n.m.r. spectrum, was assigned to C-7. The 7-oxo compound (7a) has previously been obtained from methyl podocarpate (5) by other oxidants⁸ (2,3-dichloro-5,6-dicyanobenzoquinone in alcoholic solvents or chromium trioxide in acetic acid).

The formation of compound (7a) in the foregoing thallium(III) perchlorate oxidation merits comment. Yamada *et al.*⁶ have previously observed a similar remote oxidation during the reaction of estrone with thallium(III) perchlorate. We consider that compound (7a) may be derived from compound (8), which, in the acidic medium, would be dehydrated to the quinone methide (9). Most of the known naturally occurring quinone methides⁹ contain an oxygen or other carbonyl function at the end of this quinone methide chromophore. In the remaining compounds, carbon atoms terminating the conjugated system either lack hydrogen* or form part of an aromatic system. This feature, which isolates the quinone methide chromophore from labile hydrogen atom(s), prevents their tautomeric rearrangement to phenols. Compound (9) bears labile hydrogen atoms adjacent to the quinone methide chromophore, and hence it must be very sensitive to acids and would be expected to undergo dienone–phenol rearrangement to give the phenol (10). Thallium(III) perchlorate, which is present in excess in the reaction medium, would then attack the 6,7-double bond in compound (10) from the less-hindered α -side to yield a transient bridged organothallium adduct which, on reaction with water, would change to an intermediate possessing a weak C–Ti bond. Heterolysis of the C–Ti bond would proceed with the formation of a 6,7-double bond [loss of a proton from C-7], followed by ketonization of the resulting enol, to afford compound (7a). The reaction pathway is elaborated in Scheme 1.

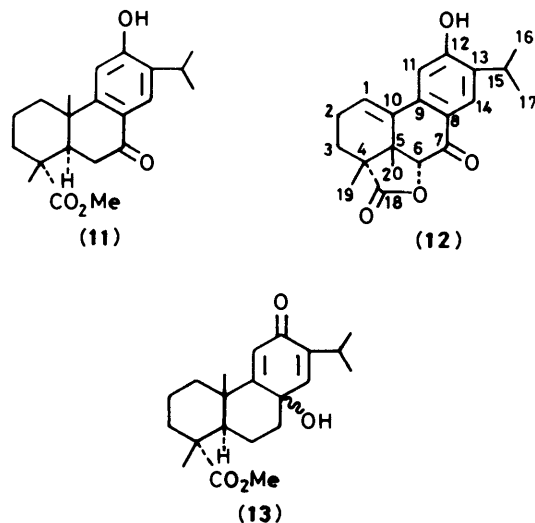
Treatment of methyl 12-hydroxyabietan-8,11,13-trien-18-oate¹⁰ (6) with thallium(III) perchlorate in diethyl ether–aqueous perchloric acid at 0 °C for 24 h yielded, after chromatography over silica gel, two products along with recovered starting material (60% yield). The first of these, $\text{C}_{21}\text{H}_{28}\text{O}_4$ [m/z 344 (M^+)], which was isolated in 5.4% yield from the 40% diethyl ether–benzene eluates, was assigned structure (11). The aromatic nature of ring c in this compound was demonstrated by the ^1H n.m.r. [δ 6.80 (1 H, s, ArH) and 7.66 (1 H, s, ArH)] as well as the u.v.¹¹ [λ_{max} (EtOH) 227 (log ϵ 4.09 and



Scheme 1.

260 nm (4.13)] spectrum. That the newly introduced oxygen atom must be present in the form of an aryl carbonyl group was indicated by the presence in the i.r. spectrum of an α,β -unsaturated carbonyl band at 1660 cm^{-1} in addition to bands at 3170 (OH) and 1744 cm^{-1} (CO_2Me). As in the case of the reaction of methyl podocarpate (5) with thallium(III) perchlorate, compound (11) must also have been formed by oxidation at C-7 remote from aromatic ring c.

The second, more polar product, $\text{C}_{20}\text{H}_{22}\text{O}_4$ [m/z 326 (M^+)], obtained in 12% yield, was eluted on the column with 70% diethyl ether in benzene. Bands at 3230 and 1685 cm^{-1} in the i.r. spectrum showed respectively that this product possessed a hydroxy and an α,β -unsaturated carbonyl group. In addition, however, this spectrum contained another carbonyl band in the form of a doublet peak at 1790 and 1750 cm^{-1} when measured in a potassium bromide disc whereas in chloroform solution this band appeared as a singlet at 1770 cm^{-1} , indicating that it was due to a five-membered ring lactone carbonyl function. The u.v. spectrum [λ_{max} (EtOH) 245 (log ϵ 4.39), 255 (4.43), 261 (4.42),



* In this respect, taxodone (2) is the first example of a naturally occurring quinone methide in which there is a labile hydrogen atom adjacent to the quinone methide chromophore. It is, however, very sensitive to acid treatment, and, indeed, under very mildly acidic conditions, dienone–phenol rearrangement occurs to give a phenol (see ref. 1).

Table 1. ^{13}C N.m.r. spectral data for compound (12) in CDCl_3

Atom	δ^a	Atom	δ^a
C(1)	131.4 (d)	C(11)	111.8 (d)
C(2)	22.6 (t)	C(12)	161.1 (s)
C(3)	25.2 (t)	C(13)	134.0 (s)
C(4)	46.6 (s) ^b	C(14)	127.0 (d)
C(5)	46.5 (s) ^b	C(15)	27.1 (d)
C(6)	82.3 (d)	C(16), C(17)	22.3 (q)
C(7)	187.9 (s)	C(18)	179.8 (s)
C(8)	122.3 (s)	C(19)	16.8 (q) ^c
C(9)	143.4 (s)	C(20)	18.8 (q) ^c
C(10)	136.8 (s)		

^a In p.p.m. downfield from internal SiMe_4 ; multiplicities given are those in the off-resonance proton-decoupled spectra. ^{b,c} Assignments may have to be interchanged.

and 300 nm (4.26)] attested to the fact that this compound was also aromatic. The ^1H n.m.r. spectrum revealed that two tertiary methyl groups [δ 1.07 (3 H, s) and 1.14 (3 H, s)] and an isopropyl group [δ 1.10 and 1.16 (each 3 H, d, J 7 Hz) and 3.13 (1 H, sept, J 7 Hz)] were present but the compound lacked a methoxy group. Signals for aromatic ring protons [δ 6.73 and 7.83 (each 1 H, s)] and two other protons [δ 4.46 (1 H, s) and 6.06 (1 H, t, J 4 Hz)] were also apparent. It seemed very likely that a five-membered lactone ring must have been formed at C-6, which is adjacent to the aryl carbonyl group at C-7, as the chemical shift of the one-proton singlet at δ 4.46 agreed with that expected for a proton on a carbon atom which is α to a carbonyl group and also bears an oxygen linkage. This proton lacked vicinal coupling, and hence C-5 must be tetra-substituted. The remaining one-proton triplet at δ 6.06 was ascribed to an olefinic proton, and the remarkable downfield shift of this signal must be the result of deshielding, presumably by the anisotropic effect of neighbouring aromatic ring c. In order to account for the preceding ^1H n.m.r. data, we postulated the migration of the angular methyl group from C-10 to C-5 with concomitant formation of a double bond between C-1 and C-10, thereby allowing us to propose structure (12) for this second product. Support for this structure was derived from the ^{13}C n.m.r. spectrum for which resonances of all carbon atoms are listed in Table 1 together with the assignment of their signals based on the off-resonance proton-decoupled spectra. Presence of both a 12-hydroxy-13-isopropylaryl ketone moiety and a five-membered lactone ring between C-6 and C-18 was verified by comparison of the ^{13}C n.m.r. spectrum of (12) with those of appropriate reference compounds.⁷ Two olefinic carbon atom signals, at δ 131.4 (d) and 136.8 (s), clearly point to the presence of a trisubstituted double bond between C-1 and C-10.

A single-crystal X -ray analysis unequivocally established the structure and stereochemistry of compound (12). The crystal structure was solved by direct methods.¹² Full-matrix least-squares refinement of atomic positional and thermal parameters converged to $R = 0.053$ over 1670 reflections. Tables of thermal parameters, interatomic distances, bond angles, and torsion angles have been deposited in Supplementary Publication No. SUP 56622 (12 pp.);* observed and calculated structure amplitudes are available on request from the Editorial office. A view of the solid-state conformations of the two crystallographically independent molecules in the asymmetric crystal unit is provided in Figure 1. Comparison of torsion angles indicates that the fused ring system have very similar conformations in both molecules, although there are slight, but

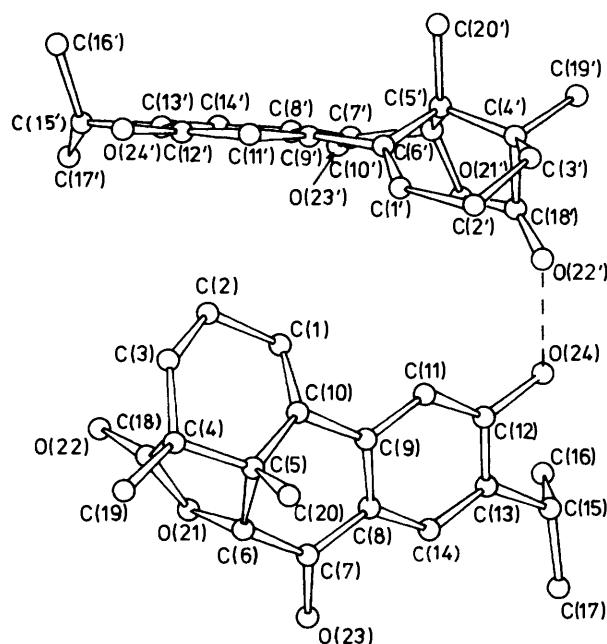
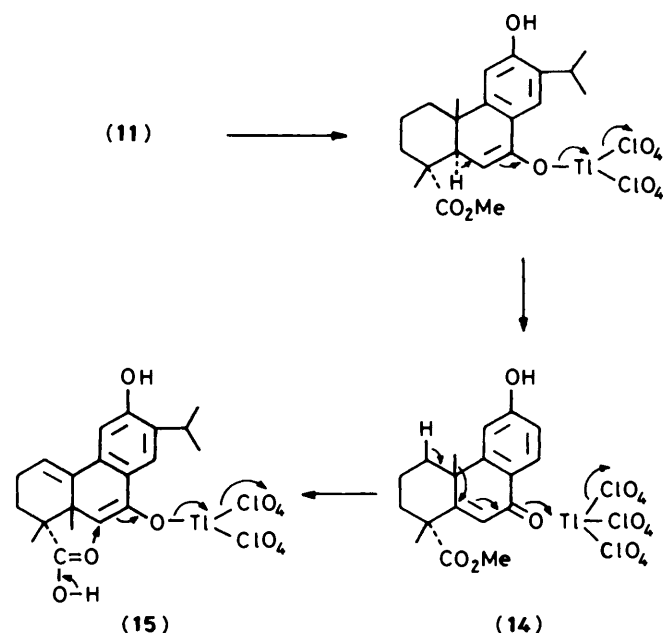


Figure. Solid-state conformations of the two crystallographically independent molecules of (12) in the asymmetric crystal unit with hydrogen atoms omitted for clarity; the broken line denotes an $\text{O-H}\cdots\text{O}$ hydrogen bond.

significant, differences in their cyclohexenone rings presumably in response to crystal packing forces, in particular to the fact that the intermolecular $\text{O-H}\cdots\text{O}$ hydrogen bonded interactions involve different C=O groups [$\text{O}(24)\cdots\text{O}(22')$ 2.73, $\text{O}(24')\cdots\text{O}(23)$ 2.73 Å]. In addition, the isopropyl substituents are quite differently oriented with respect to the aromatic ring planes in each molecule.

We propose that a plausible precursor for the formation of the lactone (12) in the thallium(III) perchlorate oxidation of compound (6) would be compound (11), which presumably



Scheme 2.

* For details of the Supplementary Publications scheme see Instructions to Authors (1986), *J. Chem. Soc., Perkin Trans. 1*, 1986, Issue 1.

arises from the as yet unisolated *p*-quinol (13), via the same reaction mechanism as proposed for formation of (7a) (see Scheme 1). In the presence of excess thallium(III) perchlorate, compound (11) would be converted into a thallium enolate from which the enone (14) would be derived. Further reaction of this enone with thallium(III) perchlorate would be followed by migration of the angular methyl group from C-10 to C-5 with concomitant formation of a double bond between C-1 and C-10 [formation of a thallium enolate* (15)]. Subsequent internal nucleophilic attack at C-6 by the acid† carbonyl group would lead to the lactone (12) (see Scheme 2).

Experimental

M.p.s were taken on a Kofler hot-stage apparatus and are uncorrected. Unless otherwise specified, i.r. spectra were recorded for KBr discs with a Perkin-Elmer 337 spectrometer, and ¹H and ¹³C n.m.r. spectra were determined for solutions in CDCl₃ with SiMe₄ as internal standard using a Varian EM3940 spectrometer and a Bruker WP-80 spectrometer operating in the Fourier transform mode, respectively. The assignment of the ¹³C signals was made by off-resonance proton decoupling. U.v. spectra were measured with a Perkin-Elmer 124 instrument. Mass spectra were determined with a DuPont 21-492B mass spectrometer at 70 eV using a direct inlet system. For column chromatography, Merck silica gel 60 (70–230 mesh ASTM) was used. Thin layer chromatograms were prepared on Merck silica gel 60 GF₂₅₄ and the spots were observed either by exposure to iodine vapour or by u.v. light. All organic extracts were dried over anhydrous sodium sulphate and evaporated under reduced pressure below 60 °C.

Reaction of Methyl Podocarpate (5) with Thallium(III) Perchlorate in Aqueous Perchloric Acid.—The thallium(III) perchlorate solution^{6b} used was prepared by dissolving thallium oxide (6.0 g) in 60% aqueous perchloric acid (100 ml) with heating at 130 °C for 2 h, followed by dilution with water (50 ml).

(a) A solution of compound (5) (1.7 g, 5.90 mmol) in methylene chloride (300 ml) was stirred with the thallium(III) perchlorate solution (140 ml, ca. 4 molar equiv.) at room temperature for 45 min. The solution was extracted with chloroform and the product obtained was chromatographed over silica gel. Starting material (400 mg, 23.5%) was recovered by elution with 25% benzene in hexane. Elution was continued with benzene and then benzene containing diethyl ether (up to 10%) to yield fractions A (350 mg, 18.6%) and B (200 mg, 11.3%). Fraction A consisted of compound (8), m.p. 209–212 °C (decomp.); δ_H 1.20 (6 H, s, 2 × Me), 3.70 (3 H, OCH₃), 5.96 (1 H,

d, *J* 2 Hz, 11-H), 6.03 (1 H, dd, *J* 10 and 2 Hz, 13-H), and 6.70 (1 H, dd, *J* 10 Hz, 14-H); δ_C[(CD₃)₂SO] 18.0 (C-17), 18.4 (C-6 or C-2), 18.8 (C-2 or C-6), 28.2 (C-15), 37.2 (C-3), 37.3 (C-10), 38.9 (C-1), 41.0 (C-7), 43.8 (C-4), 51.5 (OCH₃), 54.6 (C-5), 57.4 (C-8), 121.5 (C-11), 124.5 (C-13), 155.0 (C-14), 169.7 (C-9), 176.7 (C-16), and 186.8 (C-12) (Found: C, 70.8; H, 7.65. C₁₈H₂₄O₄ requires C, 71.02; H, 7.95%). This fraction also contained a small amount of a product which is slightly more polar than compound (8) and gave a molecular ion at *m/z* 318 in the mass spectrum, but owing to paucity of material its identity was not investigated further.

Fraction B, which is more polar than fraction A, contained compound (7a), m.p. 235–238 °C (decomp.), *m/z* 302 (*M*⁺), which was acetylated with acetic anhydride–pyridine to give compound (7b), m.p. 138–140 °C; δ_H 1.23 (6 H, s, 2 × Me), 2.26 (3 H, s, Ac), 3.66 (3 H, s, OCH₃), 6.86–7.20 (2 H, m, ArH), and 8.06 (1 H, d, *J* 8 Hz, ArH); δ_C 19.1 (C-2), 20.8 (C-17), 20.8 (CH₃CO), 28.9 (C-15), 36.4 (C-6), 37.0 (C-3), 37.5 (C-1), 38.4 (C-10), 43.3 (C-4), 48.9 (C-5), 50.9 (OCH₃), 118.5 (C-11), 120.3 (C-13), 127.9 (C-8), 128.2 (C-14), 155.0 (C-9), 156.3 (C-12), 168.8 (CH₃CO), 176.5 (C-16), and 196.6 (C-7) (Found: C, 69.55; H, 6.75. C₂₀H₂₄O₅ requires C, 69.75; H, 7.02%).

Prolonged stirring of the above reaction mixture for more than 45 min resulted in the formation of an intractable mixture of products.

(b) The above reaction was repeated at 0 °C for 24 h until all the starting material disappeared on t.l.c. The product was isolated by extraction with chloroform, and the most abundant fraction, which was obtained after column chromatography over silica gel, was submitted to preparative t.l.c. over silica gel, yielding compound (8) (230 mg, 16%) and a small amount of a compound which gave a molecular ion at *m/z* 318 (*M*⁺) in the mass spectrum but which was not investigated further.

Reaction of Methyl 12-Hydroxyabietan-8,11,13-trien-18-oate (6) with Thallium(III) Perchlorate in Aqueous Perchloric Acid.—

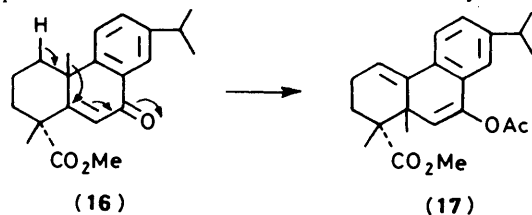
(a) A solution of compound (6) (2 g, 6.06 mmol) dissolved in the minimum amount of diethyl ether was stirred at 0 °C for 24 h with thallium(III) perchlorate solution (70 ml, ca. 3 molar equiv.). The reaction mixture was worked up with diethyl ether, and the product was chromatographed over silica gel. The fraction eluted with 10% diethyl ether in benzene yielded recovered starting material (1.2 g, 60%). Elution with 40% diethyl ether in benzene afforded compound (11) (45 mg, 5.4%), m.p. 287–289 °C (decomp.); δ_H[(CD₃)₂SO] 1.17 and 1.23 [each 3 H, d, *J* 7 Hz, CH(CH₃)₂], 1.20 (6 H, s, 2 × Me), 3.15 [1 H, sept, *J* 7 Hz, CH(CH₃)₂], 3.60 (3 H, s, OCH₃), 6.80 (1 H, s, ArH), and 7.66 (1 H, s, ArH) (Found: C, 72.95; H, 7.9. C₂₁H₂₈O₄ requires C, 73.22; H, 8.19%). Further elution with 70% diethyl ether in benzene yielded compound (12) (90 mg, 12%), m.p. 275–177 °C (decomp.) (Found: C, 73.45; H, 6.55. C₂₀H₂₂O₄ requires C, 73.60; H, 6.79%).

(b) Compound (6) (5 g, 15.1 mmol) in methylene chloride (750 ml) was stirred at 0 °C with thallium(III) perchlorate solution (357 ml, ca. 4 molar equiv.) for 6 h. After being set aside overnight at –5 °C, the solution was extracted with chloroform. The extract was evaporated and the residue was dissolved in benzene. In this case, some crystalline material (230 mg), which is soluble only with difficulty in the usual organic solvents, separated out. This relatively insoluble material was filtered off and the filtrate was subjected to chromatography over silica gel. Elution with 10% diethyl ether in benzene yielded compound (12) (1.06 g, 20.5%). In this case, compound (11) was not isolated.

Crystal Data.—C₂₀H₂₂O₄ (12), *M* = 326.40, Orthorhombic, *a* = 12.511(2), *b* = 23.861(3), *c* = 11.655(1) Å, *V* = 3479.3 Å³, *Z* = 8, *D*_{calc.} = 1.246 g cm^{–3}, μ(Cu-K_α radiation, λ = 1.5418 Å) = 6.6 cm^{–1}. Space group *P*2₁2₁(*D*₂²) uniquely from

* It is relevant to note that methyl 13-isopropyl-7-oxopodocarp-5,8,11,13-tetraen-15-oate (16) undergoes a similar rearrangement with concentrated sulphuric acid–acetic anhydride to give compound (17), as depicted in Scheme 3 (see H. Akita and A. Tahara, *Chem. Pharm. Bull.*, 1975, 23, 2660).

† In compound (15), the methoxycarbonyl group at C-4 in (14) is presumed to undergo hydrolysis in the acidic medium to give a carboxy group which would induce lactonization more efficiently



Scheme 3.

Table 2. Non-hydrogen atom fractional co-ordinates ($\times 10^4$), with standard deviations in parentheses

Atom	x	y	z
C(1)	1 818(6)	4 681(3)	1 437(8)
C(2)	1 261(7)	5 197(3)	1 005(9)
C(3)	1 950(7)	5 547(3)	231(9)
C(4)	3 124(7)	5 550(3)	585(7)
C(5)	3 608(6)	4 957(3)	693(6)
C(6)	4 561(6)	5 078(2)	1 466(7)
C(7)	5 008(6)	4 598(3)	2 157(7)
C(8)	4 365(5)	4 097(2)	2 338(6)
C(9)	3 325(5)	4 074(2)	1 896(5)
C(10)	2 855(6)	4 570(3)	1 312(6)
C(11)	2 743(5)	3 587(3)	2 077(6)
C(12)	3 153(5)	3 145(2)	2 732(6)
C(13)	4 186(6)	3 176(2)	3 203(6)
C(14)	4 769(5)	3 641(3)	2 972(6)
C(15)	4 583(6)	2 692(3)	3 945(7)
C(16)	4 073(9)	2 741(4)	5 161(8)
C(17)	5 779(7)	2 661(3)	4 029(8)
C(18)	3 299(6)	5 756(3)	1 803(7)
C(19)	3 736(7)	5 946(3)	-214(8)
C(20)	3 992(7)	4 688(3)	-442(7)
O(21)	4 145(4)	5 484(2)	2 282(5)
O(22)	2 846(6)	6 118(2)	2 309(6)
O(23)	5 930(4)	4 649(2)	2 521(5)
O(24)	2 589(4)	2 677(2)	2 907(5)
C(1')	-361(6)	3 646(2)	-481(6)
C(2')	-42(7)	3 081(3)	-924(7)
C(3')	-708(6)	2 621(3)	-390(7)
C(4')	-975(5)	2 712(2)	895(6)
C(5')	-1 554(5)	3 275(2)	1 083(6)
C(6')	-1 250(5)	3 381(3)	2 353(6)
C(7')	-1 242(6)	3 985(3)	2 746(7)
C(8')	-1 366(5)	4 431(3)	1 929(6)
C(9')	-1 296(5)	4 311(3)	757(6)
C(10')	-1 057(5)	3 734(2)	383(6)
C(11')	-1 407(5)	4 748(3)	-13(6)
C(12')	-1 556(5)	5 288(3)	363(7)
C(13')	-1 654(5)	5 421(3)	1 532(8)
C(14')	-1 545(6)	4 986(3)	2 291(7)
C(15')	-1 865(5)	6 024(3)	1 886(9)
C(16')	-2 997(7)	6 187(3)	1 798(9)
C(17')	-1 300(12)	6 208(4)	2 872(14)
C(18')	5(6)	2 796(2)	1 571(7)
C(19')	-1 558(7)	2 190(3)	1 363(9)
C(20')	-2 773(6)	3 255(3)	927(7)
O(21')	-165(4)	3 165(2)	2 439(4)
O(22')	876(4)	2 566(2)	1 478(5)
O(23')	-1 125(5)	4 059(3)	3 801(5)
O(24')	-1 631(4)	5 720(2)	-391(5)

systematic absences: $h00$ when $h \neq 2n$, $0k0$ when $k \neq 2n$, $00l$ when $l \neq 2n$. Sample dimensions: $0.04 \times 0.10 \times 0.70$ mm.

Crystallographic Measurement.—Preliminary unit-cell parameters and space group information were obtained by photographic (oscillation, Weissenberg, and precession) methods. One octant of intensity data ($\theta_{\max} = 67^\circ$, 3 483 independent measurements), recorded on an Enraf-Nonius CAD-4 diffractometer. ($\text{Cu-K}\alpha$ radiation, incident-beam graphite monochromator; ω — 2θ scans), yielded 1 670 reflections with $I > 3.0\sigma(I)$ which were retained for the structure analysis. In addition to the usual Lorentz and polarization corrections,

empirical absorption corrections were also applied to these data. Final unit-cell parameters were derived by least-squares treatment of the diffractometer setting angles for 25 moderately high order ($26^\circ < \theta < 38^\circ$) reflections widely separated in reciprocal space.

Structure Analysis.—The crystal structure was solved by direct methods.¹² Approximate co-ordinates for 44 non-hydrogen atoms were derived from an E -map, and an F_o Fourier synthesis phased by these atoms ($R = 0.42$) yielded positions for the remaining 4 atoms. Full-matrix least-squares adjustment of non-hydrogen atom positional and anisotropic thermal parameters, with hydrogen atoms included at their calculated positions in the later iterations, converged to $R = 0.053$ ($R_w = 0.067$). Final atomic positional parameters are given in Table 2; see p. 1729 for details of the availability of the other crystallographic results.

Neutral atoms scattering factors used in the structure-factor calculations were taken from ref. 13. In the least-squares iterations, $\Sigma w\Delta^2$ [$w = 1/\sigma^2(|F_o|)$, $\Delta = ||F_o| - |F_c||$] was minimized.

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